Automatica 66 (2016) 85–95

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Distributed control of inverter-based lossy microgrids for power sharing and frequency regulation under voltage constraints☆

Chin-Yao Chang, Wei Zhang [1]

Department of Electrical and Computer Engineering, Ohio State University, Columbus, OH 43210, USA

ARTICLE INFO

Article history:
Received 23 January 2015
Received in revised form
30 August 2015
Accepted 17 November 2015

Keywords:
Microgrid control
Droop control
Frequency synchronization
Power sharing
Voltage regulation

ABSTRACT

This paper presents a new distributed control framework to coordinate inverter-interfaced distributed energy resources (DERs) in island microgrids. We show that under bounded load uncertainties, the proposed control method can steer the microgrid to a desired steady state with synchronized inverter frequency across the network and proportional sharing of both active and reactive powers among the inverters. We also show that such convergence can be achieved while respecting constraints on voltage magnitude and branch angle differences. The controller is robust under various contingency scenarios, including loss of communication links and failures of DERs. The proposed controller is applicable to lossy mesh microgrids with heterogeneous R/X distribution lines and reasonable parameter variations. Simulations based on various microgrid operation scenarios are also provided to show the effectiveness of the proposed control method.

1. Introduction

Microgrids are low voltage power networks comprised of distributed generations (DGs), energy storage systems (ESSs), and loads that can operate in either grid-connected or island mode. Distributed generation contributes on-site and clean energy, which is expected to make power networks more robust, efficient and environmentally friendly (Ackermann, Andersson, & Söder, 2001; Pepermans, Driesen, Haeseldonckx, Belmans, & D'haeseleer, 2005). Energy storage systems are considered as an important resource to benefit the power networks by smoothing real time imbalance between generation and demand (Yang, Zhanget al., 2011). Some storage devices such as freewheel and battery packs can be integrated with intermittent DGs to regulate the power injection to a power network (Rajendra Prasad & Natarajan, 2006; Vazquez, Lukic, Galvan, Franquelo, & Carrasco, 2010). Demand side appliances such as plug-in hybrid electric vehicles (PHEV) and thermostatically controlled loads (TCLs) can also be viewed as energy storage resources. Those "storage" appliances can be coordinated to provide ancillary services to the main grid (Zhang, Lian, Chang, & Kalsi, 2013; Zhao, Topcu, Li, & Low, 2014; Zhao, Topcu, & Low, 2013). The proximity of DGs and ESSs to loads in a microgrid allows for a transition to the island mode during faults on the main grid. Such a transition may also be triggered by efficiency or reliability incentives, (see Nourai & Kearns, 2010; Piagi & Lasseter, 2006).

Distributed energy resources (DERs) such as DGs and ESSs connect to the microgrid through DC/AC or AC/AC inverters. During the island mode, the inverters are typically operated as voltage source inverters (VSIs). These VSIs need to be controlled cooperatively to achieve desired performance and reliability properties. In AC networks, voltage magnitude and angle difference between connected buses should be regulated in some bounded ranges for system security and stability. Frequency synchronization to a nominal value is also crucial for grid connection and stability purposes. Besides frequency and voltage regulation, sharing of active and reactive power is also considered as important control objectives in microgrids (Mohamed & El-Saadany, 2008; Schiffera, See, Raischd, & Sezie, 2016). They require that the power injection into the microgrid from DERs is proportional to the nominal value defined by economics or other incentives, while satisfying load demands (Schiffera, Ortegab, Astolfic, Raischd, & Sezie, 2013). Power sharing enables effective utilization of limited generation resources and prevents overloading (Katiraei, Iravani, Hatziargyriou, & Dimeas, 2008).

☆ This work was partly supported by the National Science Foundation under grand CCF-1331712. The material in this paper was partially presented at the 2015 American Control Conference, July 1–3, 2015, Chicago, IL, USA. This paper was recommended for publication in revised form by Associate Editor Shun-ichi Azuma under the direction of Editor Toshiharu Sugie.

E-mail addresses: chang.981@osu.edu (C.-Y. Chang), zhang@ece.osu.edu (W. Zhang).

[1] Tel.: +1 614 292 0117.

http://dx.doi.org/10.1016/j.automatica.2015.12.014
0005-1098/

To achieve the aforementioned objectives, a microgrid is typically controlled using a hierarchal structure including primary, secondary, and tertiary controls (Bidram & Davoudi, 2012; Dörfler, Simpson-Porco, & Bullo, 2014; Guerrero, Vasquez, Matas, de Vicuña, Castilla, 2011; Guerrero, Loh, Chandorkar, & Lee, 2013), which is similar to the one used in the traditional power systems. The primary droop control of a microgrid maintains the voltage and frequency stability while balancing the generation and load with proper power sharing. The secondary controller compensates the voltage and frequency deviations from their reference values. The tertiary control establishes the optimal power sharing between inverters in both islanding and grid-connected modes.

The primary droop is generally a decentralized controller that adjusts the voltage frequency and magnitude of each inverter in response to active and reactive power deviations from their nominal values. Various droop methods are proposed to achieve proportional active and reactive load power sharing (Ahn et al., 2010; Iyer, Belur, & Chandorkar, 2010; Lee, Chu, & Cheng, 2013; Mohamed & El-Saadany, 2008; Tabatabaee, Karshenas, Bakhshai, & Jain, 2011; Vasquez, Guerrero, Savaghebi, Eloy-Garcia, & Teodorescu, 2013; Yao, Chen, Matas, Guerrero, & Qian, 2011). However, this is often achieved at the cost of sacrificing other control objectives such as voltage and frequency regulation. The secondary control utilizes either centralized or decentralized communication infrastructures to restore frequency and voltage deviation induced by the primary droop. Most of the existing secondary control methods require centralized communications (He & Li, 2012; Li & Kao, 2009; Mehrizi-Sani & Iravani, 2010). On the other hand, decentralized secondary control has recently been proposed to avoid single point of failure (Shafiee, Guerrero, & Vasquez, 2014). The combined operations of the primary and secondary control require separation of time scale, resulting in slow dynamics that cannot effectively handle fast-varying loads (Simpson-Porco, Dörfler, & Bullo, 2013). In addition, the secondary control may destroy the proportional power sharing established in the primary control layer (Simpson-Porco, Dorfler, Bullo, Shafiee, & Guerrero, 2013). One possible solution is to adopt distributed or decentralized control structure for primary and secondary control layers to improve performance and support plug-and-play operation of the microgrid (Dörfler et al., 2014).

Many existing primary and secondary control methods rely on small signal linearization for stability analysis, which is vulnerable to parameter variations and change of operating points. Only several recent works (Ainsworth & Grijalva, 2013; Schiffera et al., 2013; Simpson-Porco, Dorfler, Bullo, Shafieeet al., 2013) have rigorously analyzed the stability of microgrid with droop-controlled inverters. In particular, Simpson-Porco, Dorfler, Bullo, Shafieeet al. (2013) derive a necessary and sufficient condition for the stability under primary droop control. The authors have also proposed a distributed averaging controller to fix the time scale separation issue between the primary and secondary control layers. In Ainsworth and Grijalva (2013) and Schiffera et al. (2013), stability conditions of lossless mesh microgrids have been provided. Despite their advantages, these nonlinear methods still suffer from several common limitations. First, all the nonlinear analyses mentioned above only focus on lossless microgrids with purely inductive distribution lines. The results may not be applicable for microgrids with heterogeneous and mixed R/X ratio lines, which is common in low voltage microgrids (Li & Kao, 2009). Secondly, since only frequency droop is carefully analyzed, reactive power sharing is often not guaranteed.

To address the aforementioned limitations of the existing works, we propose a distributed control framework to coordinate VSIs in an island AC microgrid. The proposed control adjusts each inverter frequency and voltage magnitude based on the active/reactive power measurements of its neighbors. We first show that the particular control structure ensures that any equilibrium of the closed-loop system results in the desired power sharing and frequency synchronization. Secondly, conditions for power sharing and synchronized frequency respecting voltage constraints are provided. The proposed controller can be applied to both radial and mesh microgrids with mixed R/X ratios. Furthermore, the proposed controller requires no separation of time scale and can tolerate reasonable parameter variations. To the authors' knowledge, most existing control framework cannot achieve active/reactive power sharing while respecting voltage and frequency regulation for a mesh microgrid with mixed R/X ratio lines.

To demonstrate the robustness of the proposed distributed controller, we also study the control performance under partial communication failures and the plug-and-play operations. We will show that as long as the communication network remains connected, all the desired properties including power sharing and frequency and voltage regulation still hold in these contingency scenarios. This effectively demonstrates the robustness of the proposed distributed controller. It is worth to mention that the proposed framework may require faster communications among the VSIs than the traditional secondary control. However, such communication requirement is reasonable for most microgrid control systems (Gungor et al., 2011; Laaksonen, 2010; Xin, Qu, Seuss, & Maknouninejad, 2011).

The rest of this paper is organized as follows. Section 2 formulates the microgrid control problem. Sufficient conditions for the solvability of the proportional power sharing problem respecting voltage constraints are also provided. The proposed distributed control framework is developed in Section 3. Robustness of the distributed controller under loss of communication links or failures of DERs is studied in Section 4. In Section 5, we validate the proposed controller through simulations under various microgrid operating scenarios, including abrupt changes of loads and loss of one VSI. Some concluding remarks are given in Section 6.

Notation. Define $\mathbb{R}_+$ and $\mathbb{R}_-$ as positive and negative real numbers, respectively. Denote $[n] := \{1, 2, \ldots, n\}$. Given a set $\mathcal{V}$, let $|\mathcal{V}|$ and $2^{\mathcal{V}}$ be its cardinality and power set, respectively. Denote the diagonal matrix of a vector x as diag(x). For a set of vectors $x_i,\ i \in \mathcal{I}$, let $\{x_i,\ i \in \mathcal{I}\}$ be the augmented vector of x_i collecting all $i \in \mathcal{I}$. Given a polyhedron $\mathcal{B} \in \mathbb{R}^n$, let $v(\mathcal{B})$ be the vertex set of $\mathcal{B}$. For a closed set $F \subseteq \mathbb{R}^n$, int(F) and ∂F are the interior and the boundary of F. The distance between a point $f \in \mathbb{R}^n$ and the set F is denoted as $d(f, F) := \inf\{\|f - \bar{f}\|_2\ |\bar{f} \in F\}$. Define $\mathbf{1}_n \in \mathbb{R}^n$ and $\mathbf{0}_n \in \mathbb{R}^n$ as the vectors with all the elements being ones and zeros, respectively. For a symmetric matrix A, let $\lambda(A)$ and $\underline{\lambda}(A)$ be the spectrum and minimal eigenvalue of A, respectively. Denote $A \otimes B$ as the tensor product between matrices A and B. Let null(A) be the null space of a matrix A.

2. Problem formulation

In this paper, we consider a connected island microgrid network as shown in Fig. 1. An island microgrid is represented by a connected and undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of buses (nodes) and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the set of distribution lines (edges) connecting the buses. The set of buses is partitioned into two parts, inverter buses $\mathcal{V}_I$ and load buses $\mathcal{V}_L$. Let $n_I = |\mathcal{V}_I|$, $n_L = |\mathcal{V}_L|$ and $n = |\mathcal{V}|$. The magnitude and phase angle of the bus voltage are denoted as E_i and θ_i, respectively. Let $x_i \triangleq [\theta_i, E_i]^T$ be the state vector at bus i, and let $x_I \triangleq \{x_i,\ i \in \mathcal{V}_I\}$ and $x_L = \{x_i,\ i \in \mathcal{V}_L\}$ be the inverter bus state vector and load bus state vector, respectively. The overall system state vector is denoted by $x = [x_I^T, x_L^T]^T$ and will be referred to as the system *voltage profile*. For each bus $i \in \mathcal{V}$, let